Subject: Lecture & Discussion Topic 1 (Message #473361)
Area: Lesson 2
From: Rob
Date: Thursday, 1-May-2003 3:21 PM

Lesson 2 Topic 1 Lecture and Discussion

The Whole Shebang: An Introduction to Our Universe

The Shape of Space

A "no aspirin required" discussion of four-dimensional space and the different possible geometries of our universe.

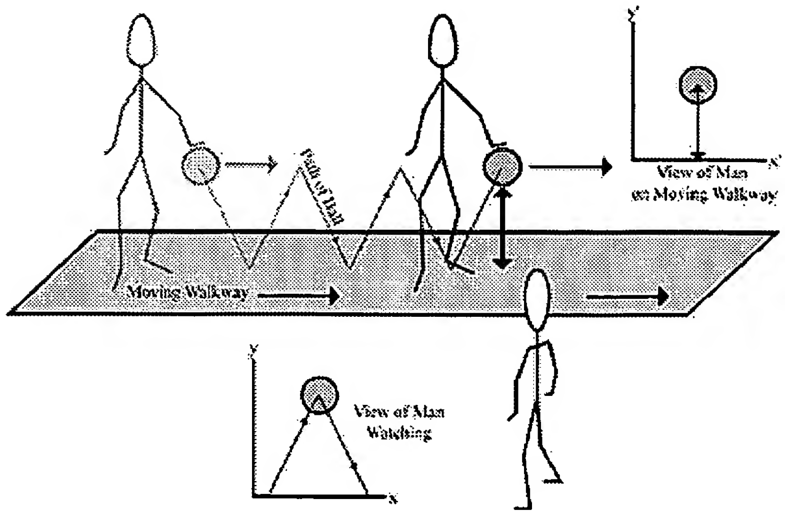
Does the geometry of the universe look like a four-dimensional horse saddle? As strange as that sounds, the answer might be yes. But what does that mean? In this lesson, you will explore the geometrical side effects of the theories of relativity and try to figure out what it means to say that space and time are curved.

Thinking in 4-D

Hubble's observations and Einstein's general theory of relativity whisked us into an expanding universe. The question is, what is the universe expanding into? Human beings visualize the in three dimensions. To understand an expanding universe, we need to see our universe as more than just X, Y, and Z. We don't think of time, the fourth dimension, as a direction – we can't move backwards in time and we can't control the rate at which we experience time. To human beings, our experience of time is a steady progression forward.

Einstein was among the first to see time as a dimension no different from the three spatial directions. To him, photons of light traced out the four-dimensional gridlines of space the way lines of ink demarcate boxes on graph paper. In this lesson, we explore what it means to live in a four-dimensional universe and the ramifications of general relativity.

To understand any type of geometry, you need to understand perspective. A person bouncing a ball sees it moving in one dimension – vertically up and down. If that person is on a moving walkway, an observer standing beside the walkway will see the ball moving in two dimensions: vertically up and down and horizontally sideways as the walkway moves. Both are observing the same ball, but each sees something different because they are in different places (Figure 2-1). An observer's perspective is referred to as a reference frame.

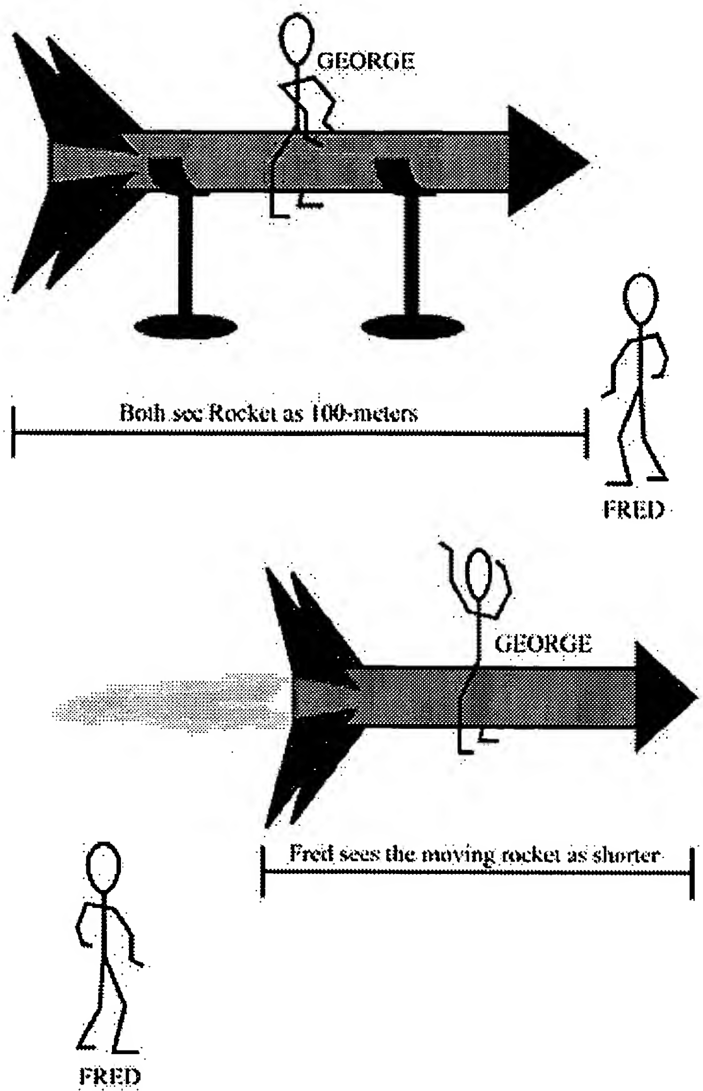


(Figure 2-1: A man bouncing a ball on a moving walkway sees the ball bouncing up and down – one-dimensional motion – while a stationary onlooker sees the ball moving both laterally and up and down – two-dimensional motion. (Graphic by Pamela L. Gay, copyright 2002))

Now, how does time work into this? Consider the following: Two guys, George and Fred, set their watches to the Weather Channel. Fred (who is not very bright) is holding a three-minute Roman candle next to his eyes. He observes it burn from 12:00 A.M. to 12:03 A.M. George is located eight light-minutes away (roughly the distance from the Earth to the Sun; see the "Light Distances" textbox below) and sees the Roman candle burn from 12:08 A.M. to 12:11 A.M. because the light takes eight minutes to reach him before he sees it. In this scenario, the two observers see the same thing happen, but their reference frames are offset in time.

It is easy to see how two observers can be offset in time, but it is harder to understand how two observers can see time pass at different rates. Einstein realized that light is observed to travel at the same rate by all observers. Imagine now that at 12:08 A.M., when the light from Fred's Roman candle reaches George, George takes off at half the speed of light relative to Fred. For George and Fred to both see the light traveling at the same speed, time must slow down for fast-moving George. If George stops and looks at his watch the instant the light finishes passing him, his watch will read 12:09 A.M. At the same instant, Fred's watch will read 12:11 A.M. While traveling at half the speed of light, George experienced time at a slower rate than stationary Fred. If George travels faster, time will appear to slow down even more as light continues to appear to move at the same rate. If George George were able to travel at the speed of light, time would stop.

As an object's speed approaches the speed of light, relativity describes many strange effects in addition to time dilation, all of which are due to the fact that light is seen to travel the same finite speed to everyone. If Fred and George go out and buy a 100-meter rocket and set it in front of their house, they can slowly measure the distance from one end of the rocket to the other. The rate that time passes for them and time passes for the rocket is the same, and they will see the rocket as 100 meters long. Now if Fred (again being the less intelligent of the two) decides to light the rocket and ride it, while George measures its length from a safe distance, they will run into problems because of of time dilation. Fred sees the rocket he is on as 100 meters long, and in its reference frame, it is always 100 meters long. To measure the length of the rocket, George measures the amount of time it takes the rocket to pass his head. Since time is passing more slowly to Fred and the rocket than to George, George measures the time it takes the rocket to pass his head (and thus its total length); then Fred measures it. This change in length and time allows them both to see the rocket moving at two-thirds the speed of light (see Figure 2-2).



(Figure 2-2: A stationary observer sees a rocket as shorter in length than an observer moving with the rocket. (Graphic by Pamela L. Gay, copyright 2002))

These ideas are not easy, but the bottom line is simple: The time measured by a single stationary observer is always shorter than the interval measured by all other observers, and the length of an object measured in the reference frame of the object is longer than the length measured by all other observers. Time dilates and length contracts. Time and space are all interwoven into a single tapestry of four-dimensional space-time.

Light Distances

When measuring large distances, it is useful to have a large measuring stick. Who would want to measure the size of the Earth in centimeters or the distance to stars in inches? Light travels at 300,000 km/sec, and astronomers use the distance light travels in different units of time to measure distances. The moon, for instance, is 384,400 kilometers away, or 1.28 light-seconds. The Sun is 149,600,000 kilometers, or 8.3 light-minutes, away.

The Math Behind Relativity

Figure 2-3 shows the Lorentz transformations (math) for time dilation and length contraction. Here is an interesting example: A wealthy businessman travels on a Concorde at exactly 2160 km/hr (0.6 km/sec) from London to New York and back. He travels a total distance of exactly 11,170 km. While he is on the Concorde, the rate time passes for him slows down relative to how his wife (who stays in London) experiences it. At the end of his flight, he will have experienced 1/10,000,000 fewer seconds!

$$x' = \frac{x - vt}{\sqrt{1 - (v/c)^2}}$$

$$t' = \frac{t - (vx/c^2)}{\sqrt{1 - (v/c)^2}}$$

(Figure 2-3: In all cases a (') denotes the moving frame. t is time, v is velocity, d is distance, and c is the speed of light (300,000,000 m/sec). (Graphic by Paméla L. Gay, copyright 2002))

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Reply

Subject: Lecture & Discussion Topic 2 (Message #473363)
Area: Lesson 2
From: Rob
Date: Thursday, 1-May-2003 3:21 PM

Lesson 2 Topic 2
Lecture and Discussion

The Whole Shebang: An Introduction to Our Universe

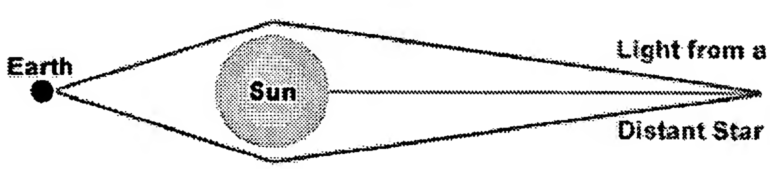
The Shape of Space

Curved Space

Einstein reformatted our view of the universe by adding a new direction. He also changed our way of looking at gravity. According to relativity theory, gravity is a consequence of curved space. Small amounts of mass cause small dips, and large amounts of mass cause large valleys in the fabric of space-time.

Let's try to understand this by first considering the path of an explorer trying to make his way from Boston to Mexico City. Our intrepid traveler takes off on a straight line, following a great circle that can take him all the way around the globe if he chooses to keep traveling. As he travels, the "straight path" he follows rises and falls as he goes over hills and down into valleys. His path also curves as the surface of the Earth curves. The traveler is confined to the surface of the Earth, and his straight path conforms to the irregularities of the Earth's surface and the curvature of the Earth's spherical geometry.

Just as our explorer is confined to the surface of the Earth, light traveling from distant objects is confined to the "surface" of space. Just as hills and valleys bend the path of our explorer, the mass of stars and galaxies – and to a much smaller extent, even the mass of human beings – causes the light's path to bend. A group of astronomers led by Arthur Stanley Eddington first observed the bending of light during an eclipse of the Sun in 1919. Normally, the sun's glare makes it impossible to observe stars in the same area of the sky as the sun. With the moon eclipsing the sun, these stars become visible and their positions relative to other stars can be measured. Eddington and company found that the starlight was bent towards the sun (see Figure 2-4). Classically, we think of the gravity of the sun bending starlight. In the framework of relativity, the light travels in a straight line and space in the vicinity of massive objects is curved.



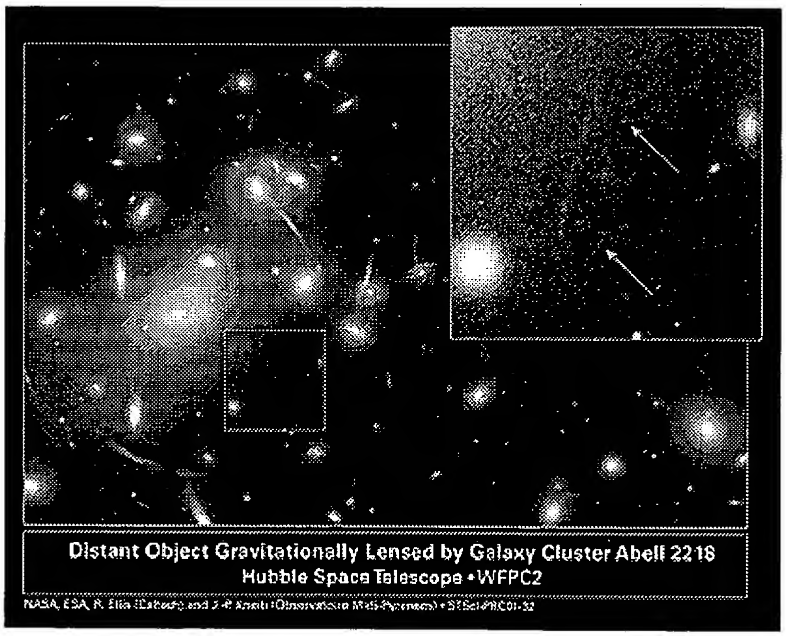
(Figure 2-4: Light rays passing near a star or other massive object are bent, causing the object producing the light to appear to be in a different place. (Graphic by Pamela L. Gay, copyright 2002))

Black Holes

The curvature of space can be used to explain black holes as being "black" because of the geometry of the space around them. Black holes are the bottomless pits of the cosmic terrain. Light rays passing too close to black holes are bent so much that they are twisted into orbit, and the light is unable to escape. The sides of the hole are too steep for anything to climb out. Like all holes, you can get within a safe distance of the edge without anything happening; however, as you get closer, the sides begin to slope in and it gets difficult to climb back from the edge – and if you get too close, you can't help falling in. Black holes do not suck in distant objects like hungry monsters; instead they consume only material that comes too close and falls in. The unsafe area around a black hole is called the Schwarzschild radius, named after a 19th-century astronomer, Karl Schwarzschild. Objects beyond this radius are able to climb away from the black hole. At the Schwarzschild radius, an object at the speed of light can escape; inside the radius, nothing, not even light, can get away.

Gravitational Lensing

Another of the observational consequences of light bending is gravitational lensing (see the textbox below). On the small scale, if a star crosses directly in front of another star, it will cause the background star to appear brighter as more light than normal from the background star is bent towards Earth. On a much larger scale, collections of galaxies, called galaxy clusters, can cause the light from background galaxies to bend, creating large arcs (see Figure 2-5).



(Figure 2-5: Light from background galaxies is bent by intervening galaxy clusters. (Graphic by Pamela L. Gay, copyright 2002))

As predicted by theory and observationally confirmed, light is seen to bend as it traverses the irregular fabric of space. The mass from stars and galaxies shapes the hills and valleys of space-time, but what of the curvature of space itself? Just as our explorer's path curves as the surface of the Earth curves, light curves to follow the curvature of space.

Gravitational Lenses

Gravitational lenses are one of the strangest and most beautiful side effects of general relativity theory. The amount of lensing – the amount that background light is arced and magnified – is directly related to the mass of the object doing the lensing. This means that astronomers can use gravitational lenses to measure the mass of distant objects. For more information, you are encouraged to read of gravitational lensing at the following Web site:

http://csep10.phys.utk.edu/astr162/lect/galaxies/lensing.html

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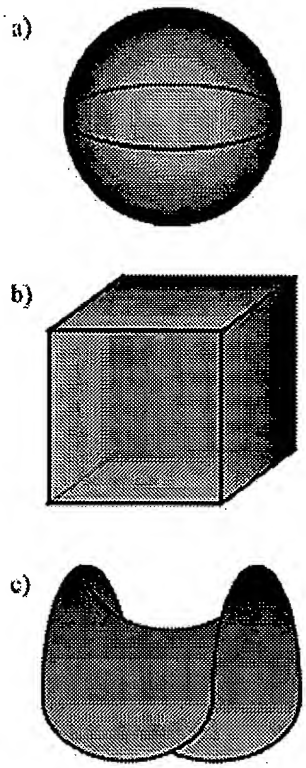
Lesson 2 Topic 3 Lecture and Discussion

The Whole Shebang: An Introduction to Our Universe

The Shape of Space

Three Possible Geometries of Expansion: Flat, Hyperbolic, Spherical

Now let's return to the question of what the universe is expanding into. It is natural for the human mind to imagine a great blob of "universe" expanding into a giant nothing. A more correct view is that of the two-dimensional surface of a balloon expanding as the balloon is blown up. To creatures living on the balloon's two-dimensional surface, all of space is expanding, but they can't see how it's expanding because they are trapped in a two-dimensional universe. We are creatures living in a three-dimensional universe that is also expanding, and like the creatures on the surface of the balloon, we can't visualize how our universe is expanding because we are in it. Einstein found that he could describe the geometry of the universe with three different geometries (see Figure 2-6): a flat cosmology, in which there is no curvature and everything expands linearly; a hypersphere (four-dimensional sphere) that curves inwards and is closed; and a hyperbolic geometry that is curved outwards and is open.



(Figure 2-6: The overall geometry of space is a four-dimensional hypersphere (a), plane (b), or hyperbolic (c) shape. (Graphic by Pamela L. Gay, copyright 2002))

The overall geometry of the universe is a result of the amount of mass in the universe. If the total mass is too high, the universe will be closed, and over time, the expansion of the universe will slow until the universe reverses direction and begins to collapse in on itself. If the total mass of the universe is too low, the universe will be open and will continue to expand forever. If the mass is just right (the so-called critical mass) the universe will be balanced between eventual collapse and constant expansion and will come to a stop, given infinite time.

Decelerating and Accelerating Expansion

Theoretically, it should be possible to determine which geometry is correct by studying how the universe is expanding and how it has expanded in the past. Scientists believe that changes in the expansion rate of the universe are caused primarily by the gravitational attraction of every object for every other object. As you read in Chapter 2 of the text, there are a number of ways to measure the distance to extra-galactic objects. By measuring the distance to and velocity of an object, we can measure how quickly the universe between the object and our galaxy is expanding. Theoretically, we can measure the current expansion rate, observe a previous expansion rate, and calculate how much the universe's expansion has slowed down. This will tell us if the universe is going to die as ice, with the universe expanding forever, or die in fire as the universe violently collapses in on itself. Currently, all observations point to a third fate: a universe with a flat geometry that is slowly grinding towards a stop.

Complicating this picture is the cosmological constant mentioned in the last lesson. Originally invoked by Einstein to stay the expansion of the universe, and then deleted as a mistake when Hubble observed all distant galaxies to be receding, the cosmological constant is back. The cosmological constant measures the energy of the vacuum of space – energy that can't be associated with any material at all – and can be measured only via its effect on the expansion of the universe. I discuss the cosmological constant and vacuum energy in more detail in Lesson 6. For now, it is important only to understand that this energy can cause the universe's expansion to accelerate, possibly inhibiting gravity from slowing the expansion rate, as it would without the vacuum energy. People who make a study of these things believe that the cosmological constant

was much higher in the early days of the universe and was responsible for an inflationary period during which the universe rapidly ballooned in size.

The Observable Volume

Observationally, we can see only the parts of the universe that are close enough that their light has had time to reach us. If the universe is 15 billion years old, we can (ignoring a bunch of scary math) see everything within a sphere with a radius of 15 billion light-years. If the universe experienced a period of rapid expansion, we will only be able to see the smallest fraction of it. This is because the expansion would have carried the majority of the universe too far away for its light to have had time to reach us. Imagine being a dust mite on a grain of sand straining your eyes to determine the shape of the Earth – this might describe the struggle faced by astronomers trying to determine the geometry of space by observing only our own small corner of it. Just as the dust mite will see the Earth as locally flat, so, too, do we see the local universe as flat. It might be impossible to understand the underlying curvature (or flatness) of space from our limited vantage point.

The universe is very busy. It is expanding outward from the big bang with a current expansion rate of about 65-70 kilometer per second. This expansion, we think, will slow due to the drag of matter attracting all other matter. At the same time, the vacuum energy of space might be accelerating the expansion of the universe. We can't know the absolute shape of space from our poor vantage point. In a flat, critical-density universe, our errant ray of light would shoot a straight line forever, while in a closed, spherical universe, it might make a Magellan's voyage back to its starting point. In an open, hyperbolic geometry, it would curve away forever.

The best we can do in trying to understand the shape of space is to measure what we can see – but the volume of space that we can see is limited by the speed of light and the age of the universe. We are trapped and – for better or worse – we are trapped in a small area that looks flat. Although this is decidedly uninteresting and it is highly improbable that the universe is perfectly balanced between eternal expansion and infernal collapse, at least an observably flat universe offers us a mathematically simple space-time geometry. Rays of light, traversing the vast expanses of space that we can observe, will bend as they pass through the gravity wells of stars and galaxies, but there might not be any additional overall curvature to twist their journey.

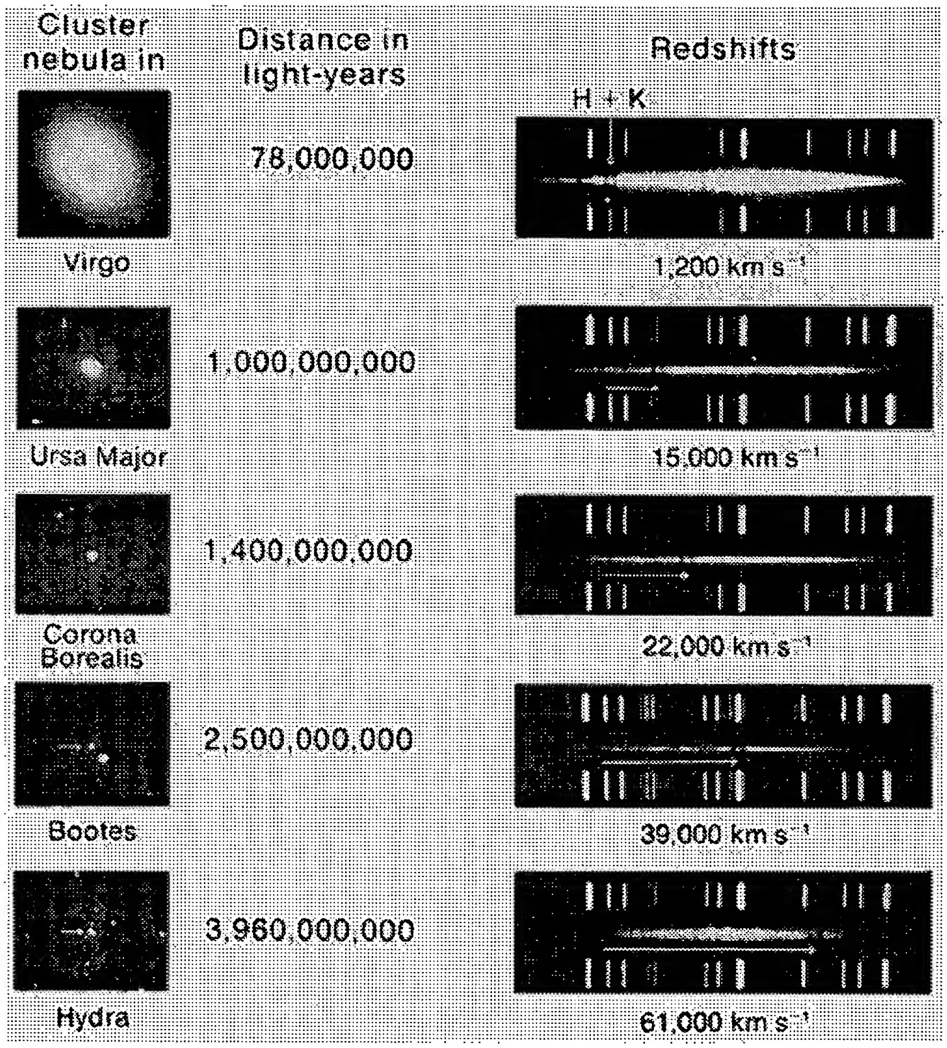
Distance Scales

One of the keys to understanding the evolution of the expansion rate of the universe is understanding how to measure distances of astronomical objects. Locally, we can measure the distances to planets using radar and the distance to nearby stars from stellar parallax. To measure distances to objects farther away, astronomers must compare how bright an object such as a variable star or a supernova appears with how luminous it actually is. To gain a deeper understanding of this topic go to:

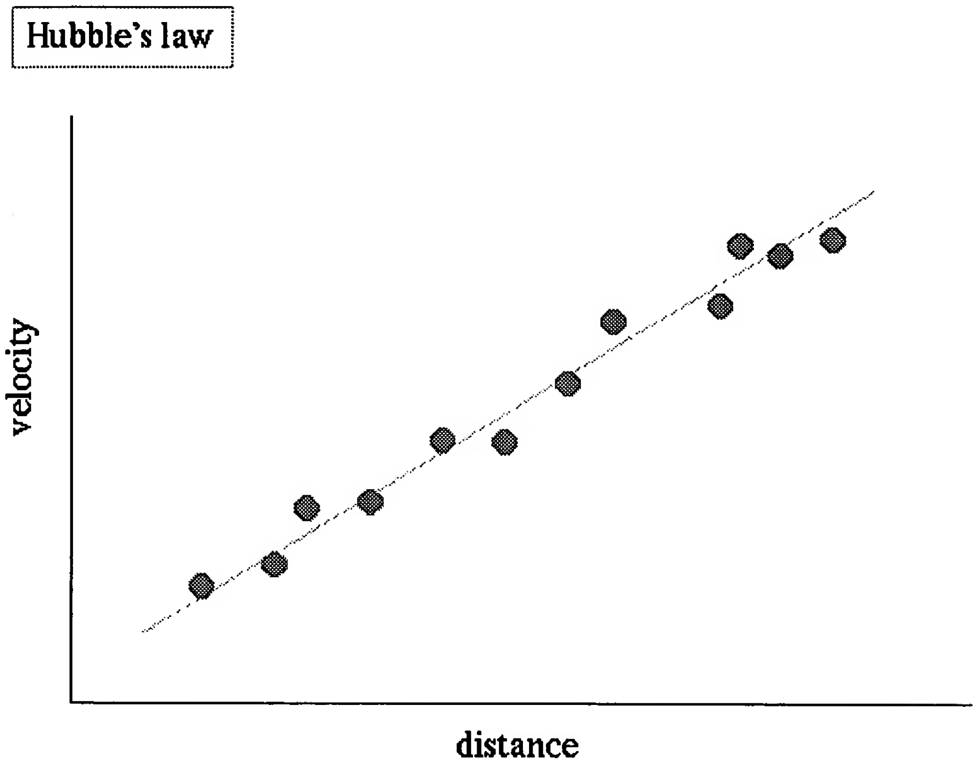
http://zebu.uoregon.edu/~js/ast123/lectures/lec14.html

Hubble's law:

In the 1930's, Edwin Hubble discoveried that all galaxies have a positive redshift. In other words, all galaxies were receding from the Milky Way.



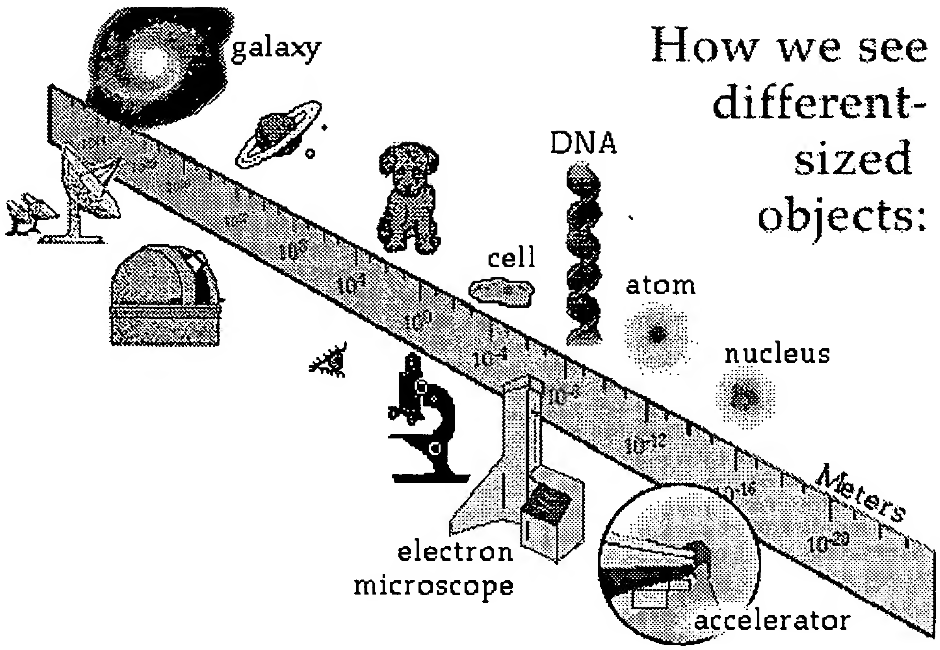
By the Copernican principle (we are not at a special place in the Universe), we deduce that all galaxies are receding from each other, or we live in a dynamic, expanding Universe.



The expansion of the Universe is described by a very simple equation called Hubble's law; the velocity of the recession of a galaxy is equal to a constant times its distance (v=Hd). Where the constant is called Hubble's constant and relates distance to velocity in units of light-years.

Distance Scale:

The most important value for an astronomical object is its distance from the Earth. Since cosmology deals with objects larger and brighter than our Sun or solar system, it is impossible to have the correct frame of reference with respect to their size and luminosity as there is nothing to compare extragalactic objects with.



Before the 1920's, it was thought that galaxies were in fact objects within our own Galaxy, possibly regions forming individual stars. They were given the name ``nebula'', which we now use to denote regions of gas and dust within galaxies.

At the turn of the century Cepheid variable stars, a special class of pulsating stars that exhibit a particular period-luminosity relation, were discovered. In other words, it was found that their intrinsic brightness was proportional to their period of variation and, hence, could be used for measuring the distances to nearby galaxies.

In the late 1920's, Hubble discovered similar Cepheid stars in neighboring galaxies as was found in our own Galaxy. Since they followed the same period-luminosity relation, and they were very faint, then this implied that the neighboring galaxies were very far away. This proved that spiral `nebula' were, in fact, external to our own Galaxy and sudden the Universe was vast in space and time.

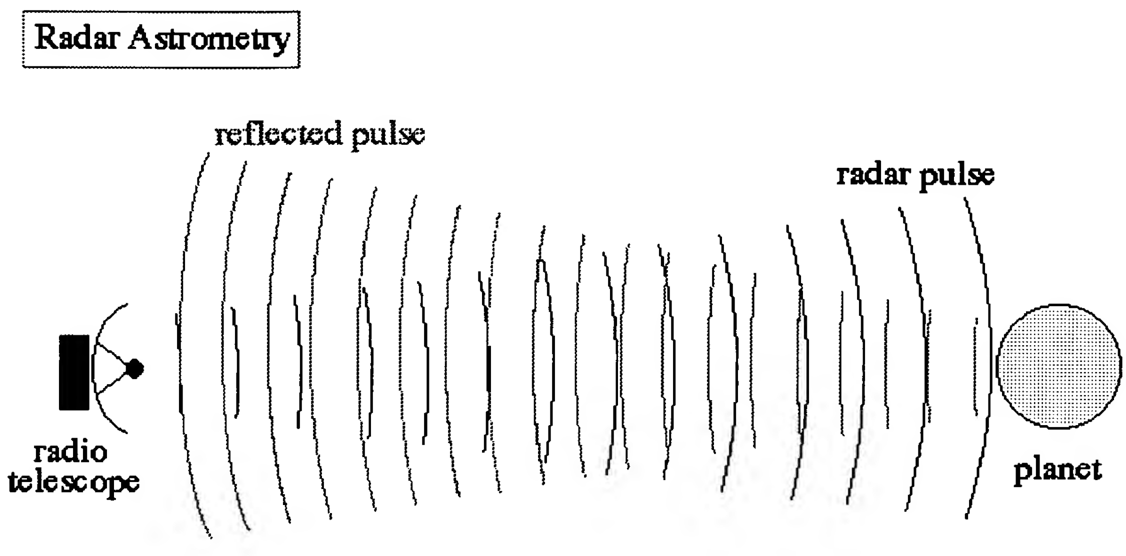
Although Hubble showed that spiral nebula were external to our Galaxy, his estimate of their distances was off by a factor of 6. This was due to the fact that the calibration to Cepheids was poor at the time, combined with the primitive telescopes Hubble used.

Modern efforts to obtain an estimate of Hubble's constant, the expansion rate of the Universe, find it necessary to determine the distance and the velocities of a large sample of galaxies. The hardest step in this process is the construct of the distance scale for galaxies, a method of determining the true distance to a particular galaxy using some property or characteristic that is visible over a range of galaxies types and distance.

The determination of the distance scale begins with the construction of ladder of primary, secondary and tertiary calibrators in the search for a standard candle.

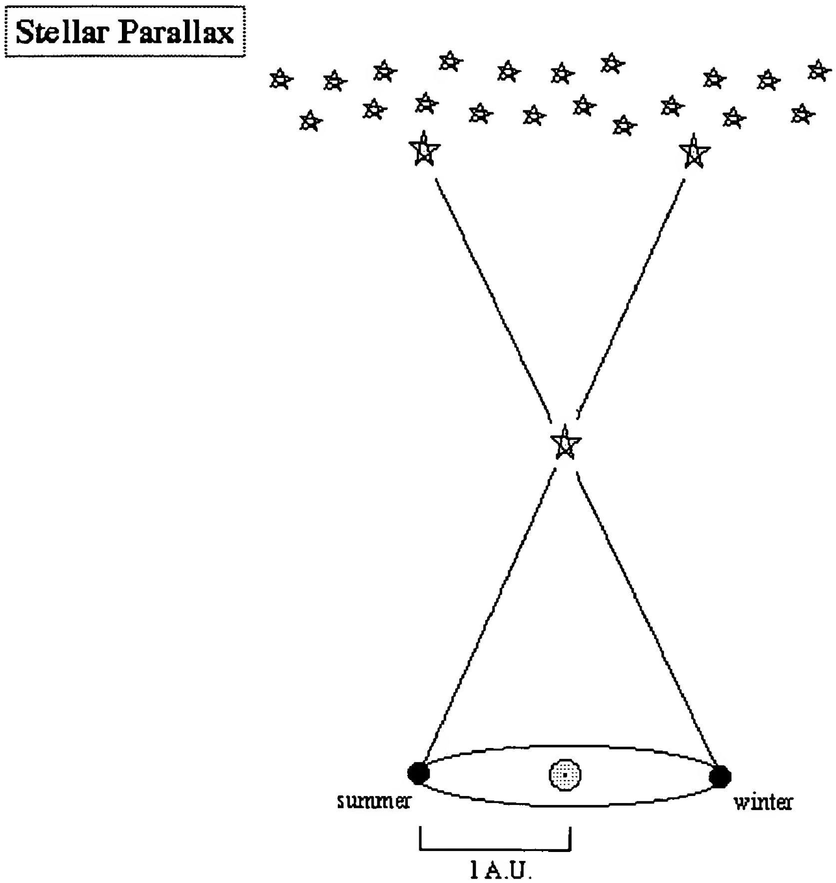
Primary Calibrators:

The construction of the distance scale ladder is a process of building of a chain of objects with well determined distance. The bottom of this chain is the determination of the scale of objects in the Solar System. This is done through radar ranging, where a radio pulse is reflected off of the various planets in the Solar System.



a radio pulse is beamed to the planet in question, and reflected pulse is detected and timed, the time of reflect times the speed of light equals the distance to the planet

The most important value from solar system radar ranging is the exact distance of the Earth from the Sun, determined by triangular measurement of the Earth and terrestrial worlds. This allows an accurate value for what is called the Astronomical Unit (A.U.), i.e. the mean Earth-Sun distance. The A.U. is the ``yardstick'' for measuring the distance to nearby stars by parallax.

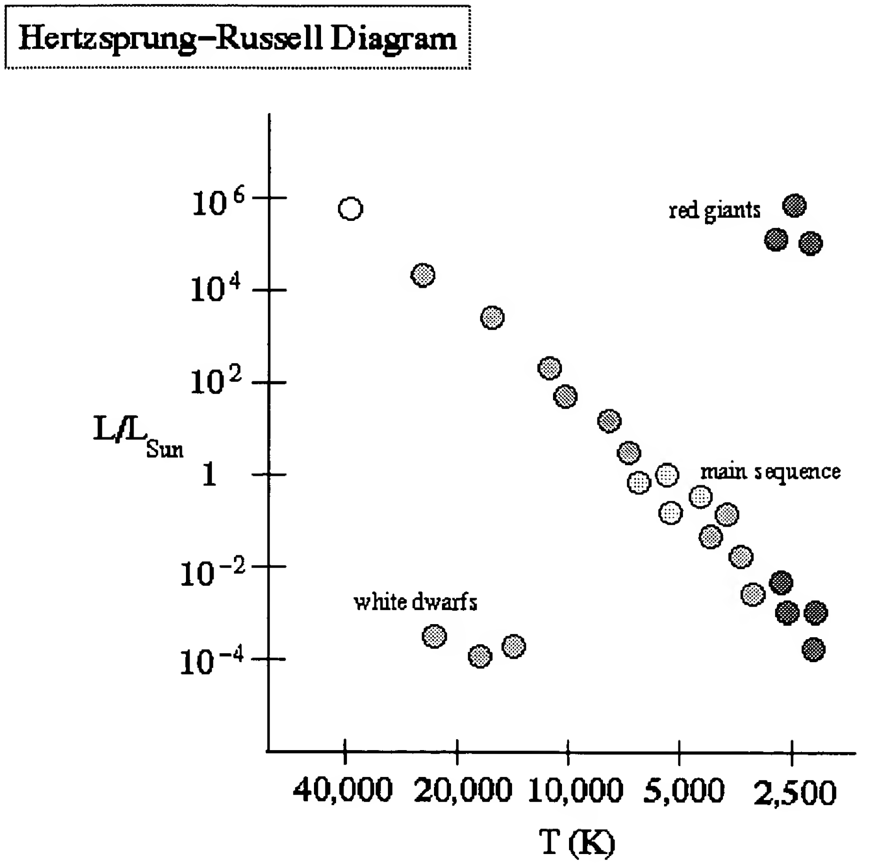


parallax is the apparent change of position of a nearby star with respect to background stars due to the motion of the Earth around the Sun

The parallax system is only good for stars within 300 light-years of the Earth due to limitations of measuring small changes in stellar position. Fortunately, there are hundreds of stars within this volume of space, which become the calibrators for secondary distance indicators.

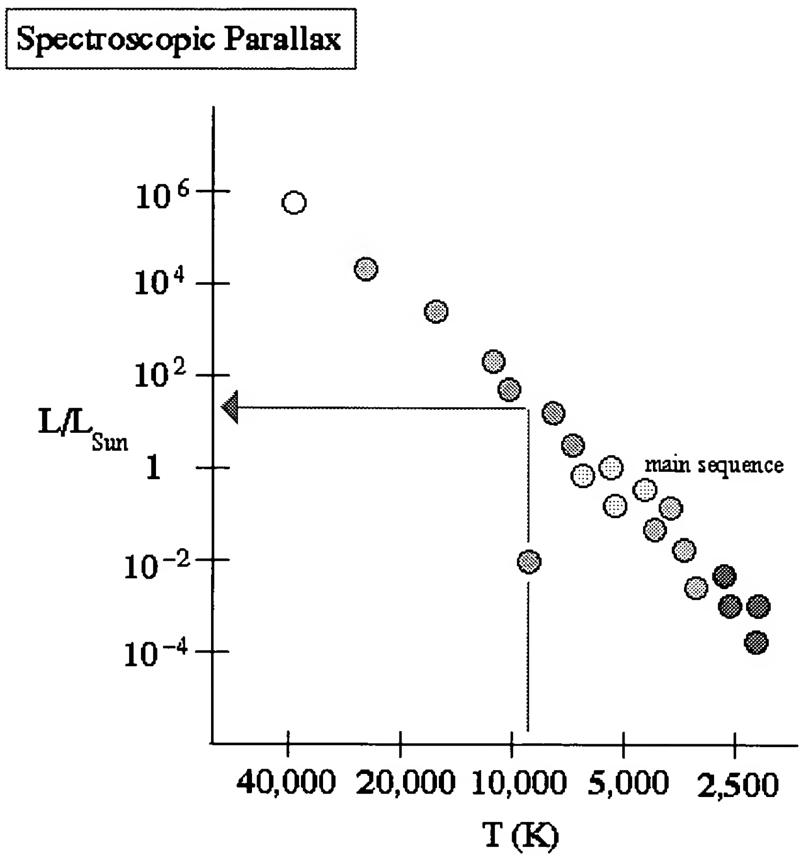
Secondary Calibrators:

Secondary calibrators of the distance scale depend on statistical measures of stellar properties, such as the mean brightness of a class of stars. It has been known since the 1800's that stars follow a particular color-luminosity relation known as the Hertzsprung-Russell Diagram.



the HR diagram is a plot of stellar luminosity (with respect to the Sun) versus stellar temperature (color). Various types of stars occupy certain parts of the diagram. Stars spend most of their lifetimes on the main sequence

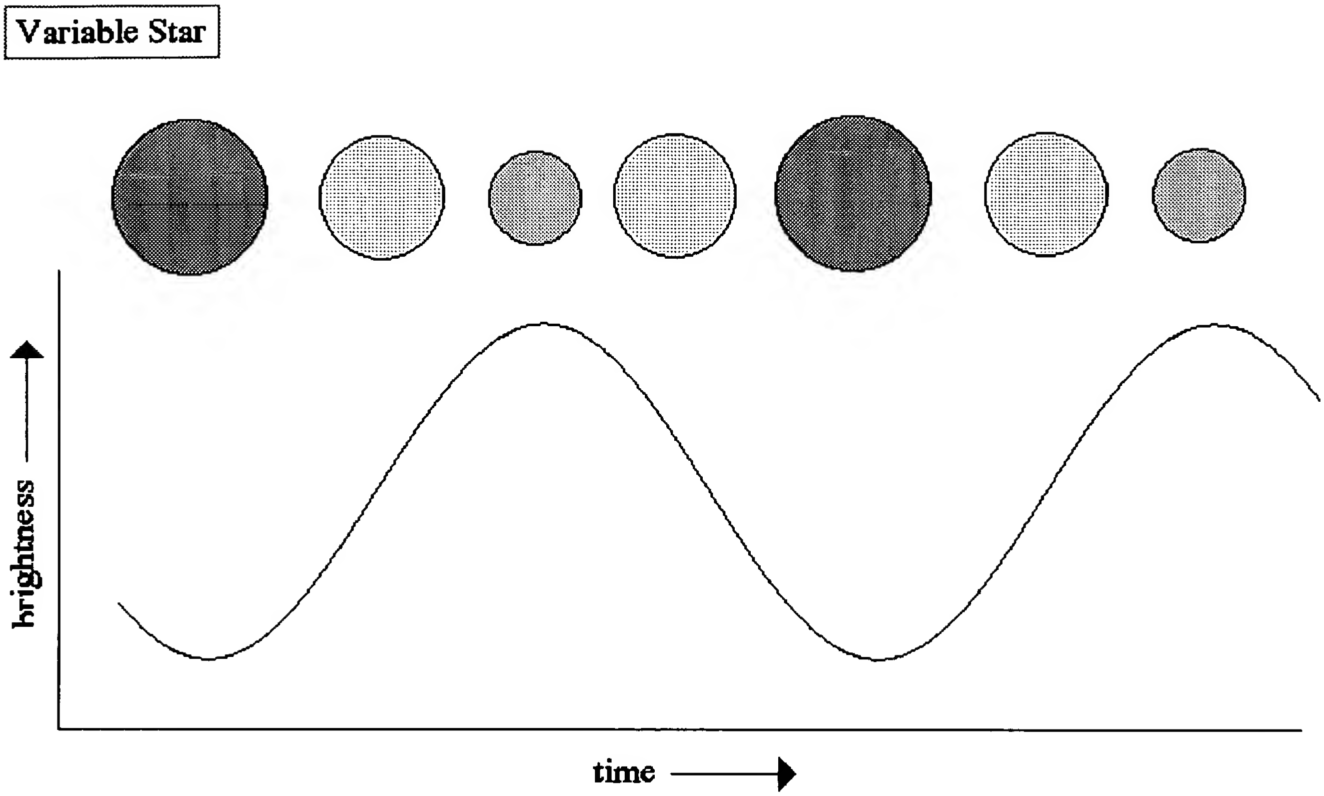
The existence of the main sequence for stars, a relationship between luminosity and color due to the stable, hydrogen-burning part of a star's life, allows for the use of spectroscopic parallax. A stars temperature is determined by its spectrum (some elements become ions at certain temperatures). With a known temperature, then an absolute luminosity can be read off the HR diagram.



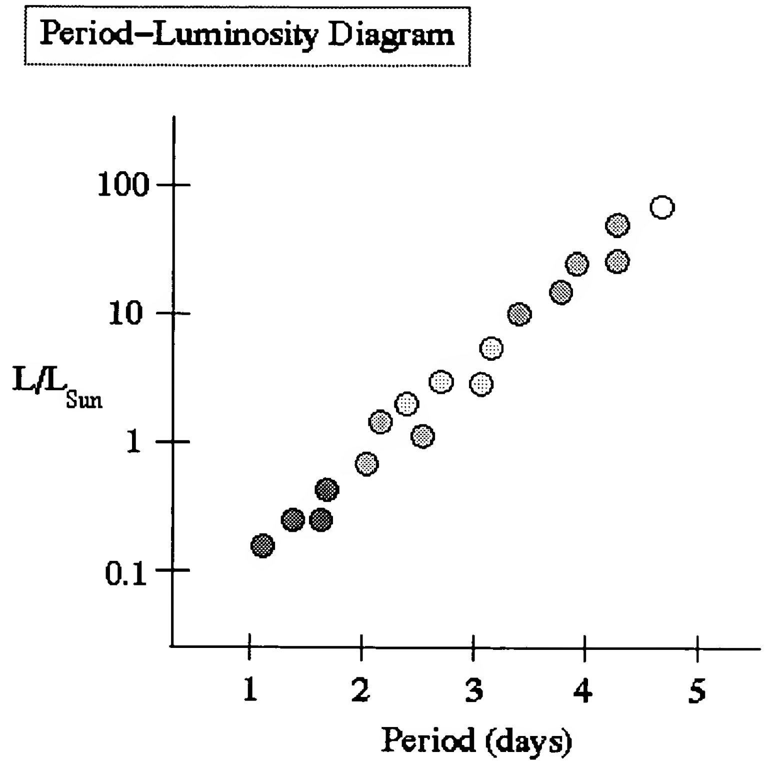
the true brightness of a star can be found if the color is known by matching the star to the main sequence. Knowledge of the observed brightness plus the true brightness derives the distance to the star.

The distance to a star is simply the ratio of its apparent brightness and its true brightness (imagine car headlights at a distance). The method allows us to measure the distances to thousands of local stars and, in particular, to nearby star clusters which harbor variable stars.

A variable star is a star where the brightness of the star changes over time (usually a small amount). This is traced by a light curve, a plot of brightness and time.



Particular variable stars, such as Cepheids, have a period-luminosity relationship. Meaning that for a particular period of oscillation, they have a unique absolute brightness.



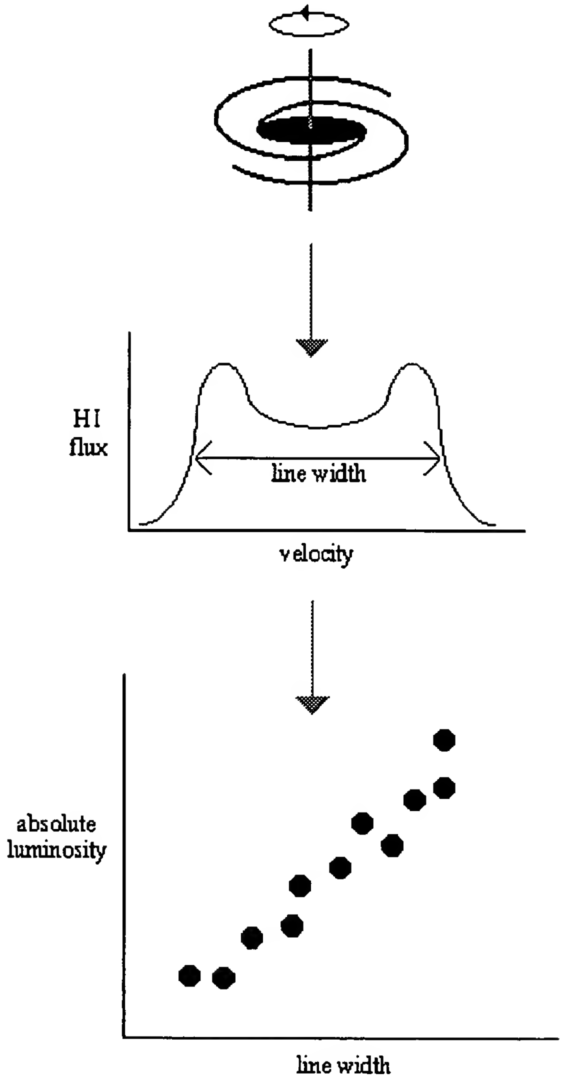
The result is that it is possible to measure the light curve of Cepheids in other galaxies and determine their distances.

Tertiary Calibrators:

The nearby region of the Universe, known as the Local Group and is located at the edge of what is known as the the Virgo supercluster of galaxies. The use of Cepheid variables is limited to within the volume of space outlined by Virgo system. Thus, the distances to nearby galaxies does not measure the true Hubble flow of the expanding Universe, but rather the gravitational infall into Virgo.

In order to determine Hubble's constant, we must measure the velocity of galaxies much farther away then the Local Group or the Virgo supercluster. But, at these distances we cannot see Cepheid stars, so we determine the total luminosity of the galaxy by the Tully-Fisher method, the last leg of the distance scale ladder.

Tully–Fisher relation



spiral galaxies rotate, and the rotation speed is proportional to the mass of the galaxy

measurements of neutral hydrogen (HI) display a ''double–horned'' profile, where the width of the line indicates the mass

a plot of line width versus absolute luminosity of a galaxy is called the Tully–Fisher relation. When calibrated using galaxies with Cepheid distances, the TF relation is used to determine Hubble's constant.

The Tully-Fisher relation is basically a plot of mass versus luminosity of a galaxy. Its not surprising that luminosity and mass are correlated since stars make up basically most of a galaxy's mass and all of the light. Missing mass would be in the form of gas, dust and dark matter.

The key parameter for this last leg of the distance scale are the calibrating galaxies to the Tully-Fisher relation, i.e. the galaxies where we know both the total luminosity from Cepheid distances and the total luminosity from the Tully-Fisher relation.

There is currently a strong debate on the value of the Hubble's constant fueled by new data from HST Cepheid studies of nearby galaxies. The community is divided into two schools of thought; 1) the old school which proposes a value for Hubble's constant around 50 to agree with the ages of the oldest stars in our Galaxy, and 2) a newer, and larger school which finds

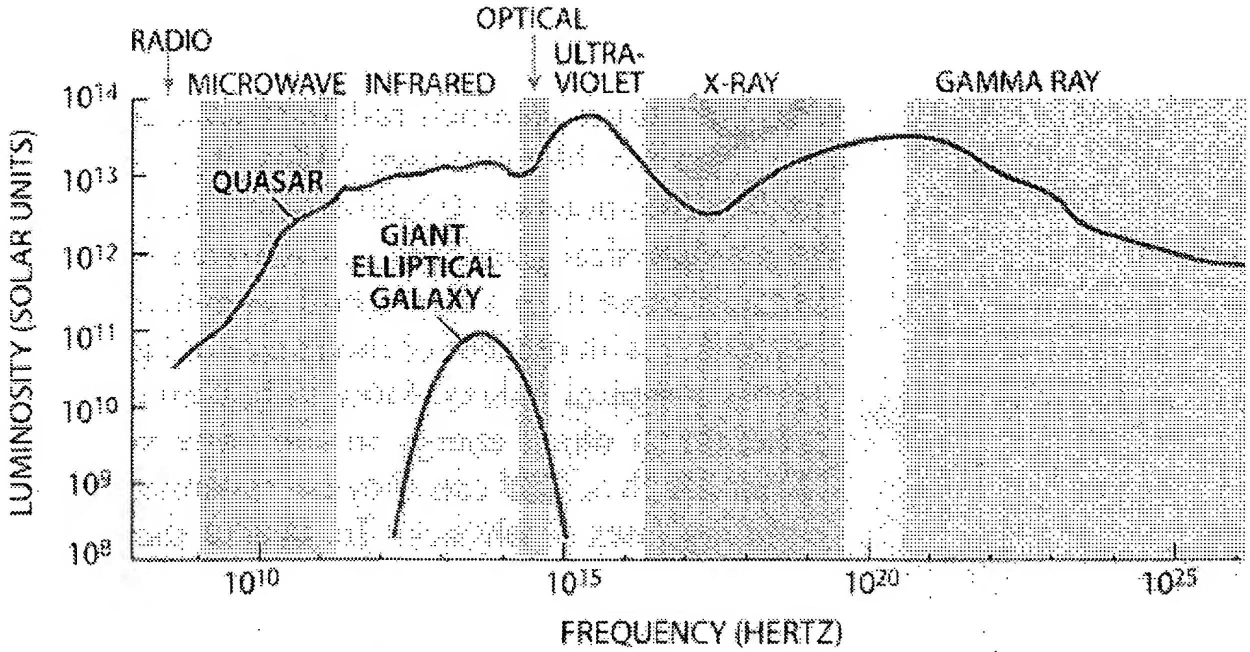
a higher Hubble's constant of 75. This higher value poses a problem for modern cosmology in that the age of the Universe from Hubble's constant is less than the age of the oldest stars as determined by nuclear physics.

So the dilemma is this, either something is wrong with nuclear physics or something is wrong with our understanding of the geometry of the Universe. One possible solution is the introduction of the cosmological constant, once rejected as unnecessary to cosmology, it has now grown in importance due to the conflict of stellar ages and the age of the Universe.

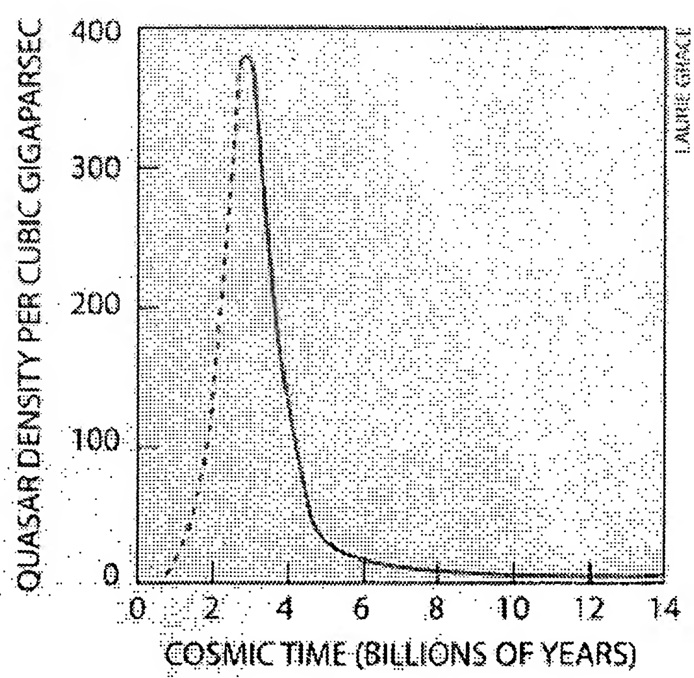
Quasars:

Quasars are the most luminous objects in the Universe. The typical quasar emits 100 to 1000 times the amount of radiation as our own Milky Way galaxy. However, quasars are also variable on the order of a few days, which means that the source of radiation must be contained in a volume of space on a few light-days across. How such amounts of energy can be generated in such small volumes is a challenge to our current physics.

Quasars were originally discovered in the radio region of the spectrum, even though they emit most of their radiation in the high energy x-ray and gamma-ray regions. Optical spectra of the first quasars in the 1960's showed them to be over two billion light-years away, meaning two billion years into the past as well.

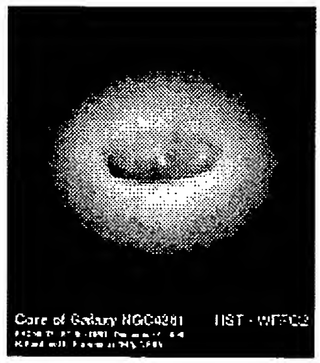


QUASAR SPECTRUM of 3C273—one of the brightest quasars and the first to be discovered—is far broader than the spectrum of a typical giant elliptical galaxy (*left*). In the optical range, the quasar is hundreds of times more luminous. Quasars were most numerous when the universe was two to four billion years old (*right*). Today quasars are 1,000 times less common. Quasars were also rare in the very early history of the universe, but the exact numbers are uncertain.



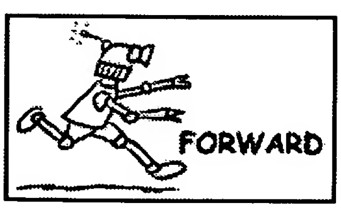
Over a thousand quasars have been discovered, most having redshifts greater than 10 billion light-years away. The number density of quasars drops off very fast, such that they are objects associated with a time when galaxies were young.

The large amount of radio and x-ray emission from quasars gives them similar properties to the class of what are called active galaxies, such as Seyfert galaxies, originally recognized by the American astronomer Carl K. Seyfert from optical spectra. Seyfert galaxies have very bright nuclei with strong emission lines of hydrogen and other common elements, showing velocities of hundreds or thousands of kilometers per second, where the high energy emission is probably due to a Galactic mass black hole at the galaxies core (for example, NGC 4261 shown below). The idea is that quasars are younger, and brighter, versions of Seyfert galaxies.



HST imaging showed that quasars are centered in the middle of host galaxies, giving more support to the idea that the quasar phenomenon is associated with Galactic mass black holes in the middle of the host galaxies. Since a majority of the host galaxies are disturbed in appearance, the suspicion is that colliding galaxies cause stars and gas to be tidally pushed into the black hole to fuel the quasar.

This process would explain the occurrence of quasars with redshift. In the far distant past there were no galaxies, so no sites for quasars. In the early phases of galaxy formation, the galaxy density was high, and there were many collisions producing many quasars. As time passed, the number of collisions decreased as space expanded and the number of quasar also dropped.



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